

A search for the fourth SM family quarks at the Tevatron

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Abstract

It is shown that the fourth standard model (SM) family quarks can be observed at the Fermilab Tevatron if their anomalous interactions with known quarks have sufficient strength.

It is known that flavor democracy [1] favors the existence of the fourth SM family fermions [2, 3, 4]. The masses of these fermions are expected to be nearly degenerate and lie between 300 GeV and 700 GeV. According to flavor democracy the fourth family neutrino should be heavy. In the framework of democratic mass matrix approach, small masses for the first three neutrinos are compatible with large mixing angles assuming that the neutrinos are of the Dirac type [5]. Obviously, the existence of the fourth SM family leads to a lot of cosmological and astrophysical consequences (see for example [6]).

The experimental lower bounds on the fourth SM family fermions are as follows [7]: 100.8 GeV for charged lepton, 45 (39.5) GeV for Dirac (Majorana) neutrino and 199 (128) GeV for "down" quark decaying via neutral (charged) current. On the other hand, the partial-wave unitarity at high energies leads to upper limit $m_4 < 1$ TeV for heavy fermions [8].

The fourth family quarks will be copiously produced at the LHC [9, 10] and the fourth family leptons will be observed at the future lepton colliders [11, 12].

In principle, the Tevatron may also contribute to the subject. First, the fourth family quarks can manifest themselves indirectly due to the enhancement in the Higgs boson production [13, 14]. Second, they can be produced directly via possible anomalous gqq_4 interactions. It should be noted that the arguments given in [15] for anomalous interactions of the top quark are more valid for u_4 and d_4 quarks since they are expected to be heavier than the top quark. In our previous papers [16, 17] we have shown that the superjet events observed by the CDF [18, 19, 20] could be interpreted in relation to the latter mechanism if one assumes, in addition, the existence of a new light scalar particle, decaying dominantly to $\tau^+\tau^-$ and/or $c\bar{c}$.

In this work, we consider the anomalous production of u_4 and d_4 quarks at the Tevatron via the subprocesses $gu(c) \rightarrow u_4$ and $gd(s, b) \rightarrow d_4$, respectively; followed by either SM or anomalous decays into the SM particles.

We use the following effective Lagrangian for the anomalous interactions of the fourth SM family quarks [16]:

$$L = \frac{\kappa_\gamma^{q_i}}{\Lambda} e_q g_e \bar{q}_4 \sigma_{\mu\nu} q_i F^{\mu\nu} + \frac{\kappa_Z^{q_i}}{2\Lambda} g_Z \bar{q}_4 \sigma_{\mu\nu} q_i Z^{\mu\nu} + \frac{\kappa_g^{q_i}}{\Lambda} g_s \bar{q}_4 \sigma_{\mu\nu} T^a q_i G_a^{\mu\nu} + h.c. \quad (1)$$

where $F^{\mu\nu}$, $Z^{\mu\nu}$, and $G^{\mu\nu}$ are the field strength tensors of the photon, Z boson and gluons, respectively; T^a are Gell-Mann matrices; e_q is the charge of the quark; g_e , g_Z , and g_s are the electroweak, and the strong coupling constants, respectively. $g_Z = g_e / \cos \theta_W \sin \theta_W$ where

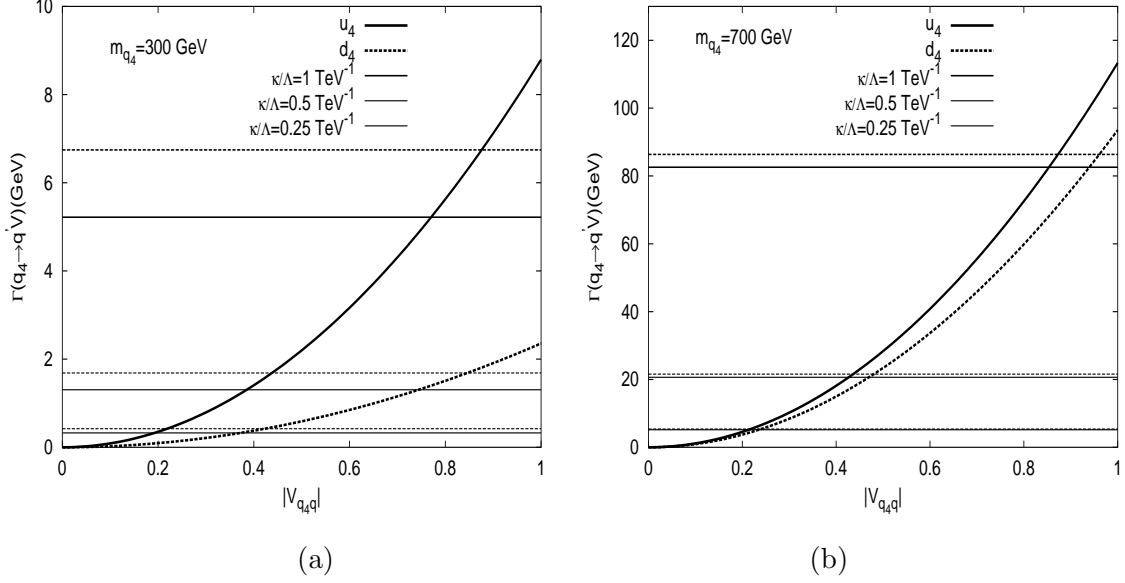


FIG. 1: The decay widths for the fourth family quarks with mass a) $m_{q_4} = 300$ GeV and b) $m_{q_4} = 700$ GeV. Horizontal lines correspond to the anomalous decay modes.

θ_W is the Weinberg angle. $\kappa_{\gamma,Z,g}^q$ define the strength of the anomalous couplings for the neutral currents with a photon, a Z boson and a gluon, respectively; Λ is the cutoff scale for the new physics.

In order to calculate the cross-sections and the decay widths, we have implemented the new interaction vertices into the CompHEP [21] package. We have used the parton distribution functions CTEQ5L [22] at $Q^2 = m_{q_4}^2$. In addition to the dependence on the fourth family quark masses, the decay widths depend on $\kappa_V^{q_i}$ for anomalous decays and on CKM matrix elements $V_{q_4 q}$ for SM decay modes. This is demonstrated in Fig. 1a(b) for $m_{q_4} = 300$ GeV (700 GeV). Since u_4 and d_4 quarks are almost degenerate in mass, their anomalous s -channel production cross sections will be of the same order for equal anomalous couplings. If the SM decay modes of the fourth family quarks are dominant, an investigation of u_4 quark is advantageous because of the clear $u_4 \rightarrow bW^+$ signature comparing to $d_4 \rightarrow tW^- \rightarrow bW^+W^-$. If the anomalous decay modes are dominant d_4 quark has a clear signature $d_4 \rightarrow bV$ ($V = \gamma, Z, g$) with b -tagging. Corresponding Feynman diagrams are shown in Fig. 2.

First, let us consider the process $p\bar{p} \rightarrow u_4 X \rightarrow bW^+ X$. Table I lists the cross sections for signal (with couplings $\kappa/\Lambda = 0.5 \text{ TeV}^{-1}$ and 0.25 TeV^{-1}) and the main background

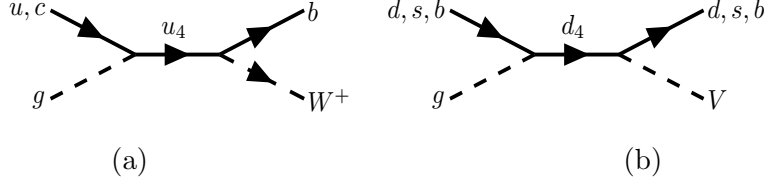


FIG. 2: Anomalous production of q_4 quarks followed by a) SM decay of u_4 quark and b) anomalous decay of d_4 quark where $V = g, Z, \gamma$.

TABLE I: The cross sections for the process $p\bar{p} \rightarrow u_4 X \rightarrow bW^+ X$ with $\kappa/\Lambda = 0.5$ and 0.25 TeV^{-1} , and the corresponding background $p\bar{p} \rightarrow bW^+ X$ without and with p_T cuts.

$m_{u_4} = 300 \text{ (700) GeV}$				
	no cut		with cut	
$\kappa/\Lambda, \text{ TeV}^{-1}$	0.5	0.25	0.5	0.25
$\sigma_{S+B}, \text{ pb}$	22.1 (0.62)	5.7 (0.21)	20.4 (0.34)	5.2 (0.082)
$\sigma_B, \text{ pb}$	0.184		6.8×10^{-4}	

$p\bar{p} \rightarrow bW^+ X$. We consider two cases: without any cuts and with $p_T^b > 50 \text{ GeV}$ for b-jets for two limiting m_{u_4} mass values, namely, 300 GeV and 700 GeV. Numerical calculations were performed for $|V_{u_4 b}| = (\kappa/\Lambda) \cdot \text{TeV}$. This yields the dominance of SM decay mode (see Fig. 1). In order to estimate the observability limits for anomalous couplings κ/Λ , we use the definition of significance

$$SS = \frac{\sigma_{S+B} - \sigma_B}{\sqrt{\sigma_B}} \sqrt{\epsilon \cdot BR \cdot L_{int}} \quad (2)$$

where $\epsilon = 0.5$ is the detection efficiency including b-tagging and $BR = 0.2$ is the branching ratio of $W^+ \rightarrow e^+ \nu_e + \mu^+ \nu_\mu$. We also require the minimum number of signal events to be 10 and $SS \geq 5$. Assuming $L_{int} = 10 \text{ fb}^{-1}$ for integrated luminosity. We obtain following low limits on the anomalous coupling: $\kappa/\Lambda = 0.03 \text{ TeV}^{-1}$ without cuts and $\kappa/\Lambda = 0.01 \text{ TeV}^{-1}$ with $p_T^b > 50 \text{ GeV}$ for $m_{u_4} = 300 \text{ GeV}$. Corresponding numbers for $m_{u_4} = 700 \text{ GeV}$ are $\kappa/\Lambda = 0.33 \text{ TeV}^{-1}$ and $\kappa/\Lambda = 0.12 \text{ TeV}^{-1}$, respectively.

The next process we consider is $p\bar{p} \rightarrow d_4 X \rightarrow qV X$ where $q = d, s, b$ and $V = g, Z, \gamma$. The condition $|V_{d_4 t}| < (\kappa/\Lambda) \cdot \text{TeV}$ ensures the anomalous decay mode of d_4 to be dominant. In Table II, branching ratios and total decay widths of d_4 quark with $m_{d_4} = 300$ and 700 GeV are given for the anomalous coupling $\kappa/\Lambda = 0.5 \text{ TeV}^{-1}$ and $\kappa/\Lambda = 0.25 \text{ TeV}^{-1}$. The

TABLE II: Branching ratios (BR) and decay widths Γ for d_4 quark with the anomalous coupling $\kappa/\Lambda = 0.5$ and 0.25 TeV^{-1} . The last row presents the cross section for anomalous production of d_4 quarks.

$m_{d_4}, \text{ GeV}$		300		700	
$\kappa/\Lambda, \text{ TeV}^{-1}$		0.5	0.25	0.5	0.25
	$gd(s, b)$	31	31	31	31
BR(%)	$Zd(s, b)$	1.9	1.9	2.1	2.1
	$\gamma d(s, b)$	0.17	0.17	0.16	0.16
$\Gamma, \text{ GeV}$		1.75	0.44	22.4	5.6
$\sigma(p\bar{p} \rightarrow d_4 X), \text{ pb}$		21.4	5.19	0.18	0.077
$\sigma(p\bar{p} \rightarrow b\gamma X), \text{ pb}$		2.72×10^{-3}		2.25×10^{-6}	

calculated signal cross sections for d_4 quark are presented in the last row of the Table II.

Keeping in mind the assumptions for the decays of u_4 and d_4 quarks, one can differentiate between u_4 and \bar{u}_4 quarks by identifying the charge of the lepton from W decay. However, d_4 and \bar{d}_4 quarks have the same final state signatures. For this reason we will double the number of signal events in our estimations below. The decay modes of d_4 and \bar{d}_4 quarks consist of two-jet, Z +jet and γ +jet. Even though the dijet mode is dominant, the extraction of the signal doesn't seem to be promising due to the huge SM background. For the Z +jet mode, again $Z \rightarrow q\bar{q}$ is not promising due to the large background; $BR(Z \rightarrow l^+l^-)$ reduces the number of events a lot; $Z \rightarrow \nu\bar{\nu}$ results in mono-jet final states but one cannot reconstruct m_{d_4} . Hence, the optimum final state is γ +jet. The background for this process is also large but, it can be reduced if one uses the advantage of b-tagging. For this reason we consider the signal process $p\bar{p} \rightarrow d_4 X \rightarrow b\gamma X$ with the main background $p\bar{p} \rightarrow b\gamma X$.

For illustration, in Fig. 3 we present the invariant mass distribution of the background and signal events for $m_{d_4} = 300 \text{ GeV}$, and two values of κ/Λ (0.5 and 0.25 TeV^{-1}). Obviously, from Fig. 3 the signal is quite observable. As κ/Λ decreases and/or m_{d_4} increases the situation gets worse. In order to observe at least 10 signal events with $SS \geq 5$ at $L_{int} = 10 \text{ fb}^{-1}$, the anomalous coupling should satisfy $\kappa/\Lambda \geq 0.08$ (0.9) TeV^{-1} for $m_{d_4} = 300 \text{ GeV}$ ($m_{d_4} = 700 \text{ GeV}$).

In conclusion, the fourth SM family quarks could be observed at the upgraded Tevatron

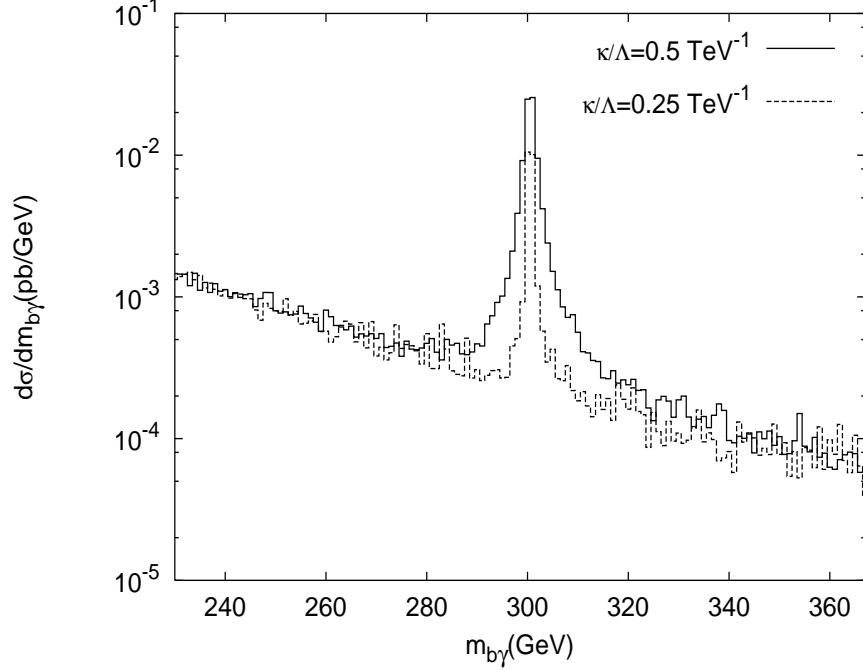


FIG. 3: Invariant mass distribution of b-tagged jet and photon for signal ($m_{d_4} = 300$ GeV, $\kappa/\Lambda = 0.5$ and 0.25 TeV^{-1}) and background.

depending on the anomalous coupling and the mass values. For $L_{int} = 10 \text{ fb}^{-1}$, u_4 quark with mass 300 GeV and SM decay mode can be observed if $\kappa/\Lambda > 0.01 \text{ TeV}^{-1}$. For $m_{u_4} = 700$ GeV, the lower limit on κ/Λ is 0.12 TeV^{-1} . On the other hand, d_4 quark with mass 300 (700) GeV and anomalous decay mode can be observed if $\kappa/\Lambda > 0.08$ (0.9) TeV^{-1} .

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